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Application of: Shum et al.

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For: METHOD AND APPARATUS FOR  
RECOVERING A THREE-DIMENSIONAL  
SCENE FROM TWO-DIMENSIONAL  
IMAGES

Examiner: Allen C. Wong

Art Unit: 2613

Attorney Reference No. 3382-52053

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I.	REAL PARTY IN INTEREST	3
II.	RELATED APPEALS AND INTERFERENCES	3
III.	STATUS OF CLAIMS	3
IV.	STATUS OF AMENDMENTS	3
V.	SUMMARY OF THE INVENTION	3
VI.	ISSUES	5
VII.	GROUPING OF CLAIMS	5
VIII.	ARGUMENT	6
	A. Rejection of claims 1-37 under 35 U.S.C. § 102(e)	6
IX.	CONCLUSION	4
	APPENDIX A	15

**I. REAL PARTY IN INTEREST**

The real party in interest is Microsoft Corporation, by an assignment from the inventors recorded at Reel 010184, Frame 0776.

**II. RELATED APPEALS AND INTERFERENCES**

Currently, there are no other pending appeals or interferences known to appellant, the appellant's legal representatives, or assignees, which will directly affect or be directly affected by or have a bearing on the pending appeal.

**III. STATUS OF CLAIMS**

Claims 1-37 remain rejected under 35 U.S.C. § 102(e) as being anticipated by *Moriya et al.*, U.S. Pat. No. 6,046,745 ("*Moriya*") and remain appealed in conjunction with which the subject Appeal Brief is being filed.

**IV. STATUS OF AMENDMENTS**

A qualifying amendment was filed on January 30, 2003 and was entered. An amendment after final rejection was filed on August 7, 2003 but the amendment was not entered. Thus, for the purpose of Appeal the claims will be presented as they appeared after the entry of the first amendment filed on January 30, 2003.

**V. SUMMARY OF THE INVENTION**

The field of computer graphics has made significant strides in recent years by improving upon the processing required to recreate real life objects in terms of their motion, color and other appearance characteristics. One of the challenges in faithfully depicting real life objects is that in real life objects appear in terms of three dimensions (3D) (e.g., in x, y, and z dimensions), whereas the capture and display of images of such objects may be in terms of two dimensions (2D) (e.g., in x and y dimensions). Thus, the specification describes an invention which generally relates to three-dimensional computer graphics, and, more particularly, relates to reconstructing a realistic three-dimensional scene from a sequence of two-dimensional images. See, specification at page 1, lines 5-7.

A 3D scene that is displayed to a user may be generated from a synthetic 3D scene, which is generated by a computer, or a real scene, which can be captured using a camera (e.g., video camera). *See*, specification at page 2, lines 1-9. For either synthetic or real scenes, there are different parameters associated with the scene, such as the 3D structure associated with any object in the scene and the camera movement (e.g., rotation and translation) for a real or imaginary camera capturing the scene. *Id.* Thus, it is desirable to automatically recover the structure of a 3D scene together with 3D camera positions from a sequence of images (e.g., video images) acquired by an unknown camera undergoing unknown movement. *Id.* Once a 3D structure is recovered it can be used to generate a complete 3D computer model of the object, which can be used to illustrate a different perspective of the object in 3D space. *See*, specification at page 1, lines 23-29. On a 2D display, different perspectives may then be used to show different lighting and shadowing changes in order to create a perception of viewing an object in 3D. *Id.*

Recovering a 3D scene from a sequence of images is often accomplished using structure-from-motion (SFM) algorithms. *See*, specification at page 2, lines 10-21. Over the years, various SFM have been proposed and studied extensively because of their applications in robotics, video editing and image based modeling and rendering. *Id.* Some important aspects of SFM calculations include identifying multiple feature points in images, using a long baseline, and efficient bundle adjustment. *Id.* A feature point is any point in the image that can be tracked well from one frame to another. *Id.* Typically, corners of an object are easily identifiable and are considered good feature points. *Id.* The base line is associated with the motion of a camera in relation to an object depicted in an image. *Id.* Bundle adjustment is a non-linear minimization process that is typically applied to the entire collection of the input frames and features of the input image stream. *Id.* Essentially, bundle adjustment is a non-linear averaging of the features over the sequence of input frames to obtain the most accurate 3D structure and camera motion. *Id.*

There are, however, problems with conventional 3D reconstruction using SFM. For example, bundle adjustment of long sequence of input frames may be computationally expensive if it involves processing the entire sequence of input frames and features at once. *See*, specification at page 2, line 22 – page 3, line 2. Additionally, the bundle adjustment used in 3D reconstruction requires a good initial estimate of both the 3D structure and the camera motion.

*Id.* The complexity of interleaving bundle adjustment for each iteration step may be measured as a function of the number of feature points and the number of frames being bundled. *Id.* Thus, bundle adjustment computed over a long sequence of input frames is time consuming and slows the entire 3D reconstruction. *Id.* For this reason, most systems use relatively short or sparse set of image sequences. *Id.* In practice, however, structure from motion (SFM) is often applied to a long sequence of images in order to achieve better 3D reconstruction. *Id.*

To overcome the shortcomings of conventional 3D reconstruction, a long sequence of frames or images may be divided into a number of smaller segments with each segment comprising a subset of the longer sequence of frames. *See*, specification at page 3, lines 10-14. A 3D reconstruction can then be performed on each segment individually. *Id.* Later on, the 3D reconstruction of all the segments can be combined together through an efficient bundle adjustment to complete the 3D reconstruction for entire sequence of input frames. *Id.* Since the complexity and hence, the computational cost of 3D reconstruction and bundling are directly affected by the number of frames being processed, segmenting a longer sequence of frames is one manner in which these costs can be significantly reduced. *Id.*

Further improvement may be realized by reducing the number of frames in each sequence by creating virtual key frames to encode the 3D structure for each segment. *See*, specification at page 3, lines 15-20. Also, the segmenting of the sequence of frames may be made more efficient by generating segments wherein the number of frames per segment is based on the number of feature points present in each frame in the segment. *Id.* at 21-27. Thus, each segment may vary in the number of frames contained within. *Id.* For example, any frame that has less than a threshold number of feature points may be moved to a different segment. *Id.* This approach to segmenting balances the desire for a long baseline and a small tracking error. *Id.*

## **VI. ISSUES**

The single issue presented for review is whether claims 1-37 (as amended in the amendment filed on January 30, 2003) are patentable under 35 U.S.C. § 102(e) over *Moriya*.

## **VII. GROUPING OF CLAIMS**

Independent claims 1, 9, 23, 31, 36 and 37 and any of their respective dependent claims each contain different limitations that further distinguish each from the prior art. However, to

facilitate the Board's consideration of this appeal, Applicants group the claims for the purposes of this appeal as follows:

For the purposes of this appeal only, patentability of claims 2-8 and 23-37 stand or fall with the patentability of claim 1 and patentability of claims 10-22 stand or fall with the patentability of claim 9.

## VIII. ARGUMENT

### Rejection of claims under 35 U.S.C. § 102 (e)

Applicants respectfully request reversal of the Examiner's rejection of claims 1-37 under 35 U.S.C. § 102(e) as being anticipated by *Moriya*. To anticipate a claim, the reference must teach or suggest each and every element of the claim. *See* MPEP § 2131. More particularly, "A claim is anticipated only if each and every element as set forth in the claim is found, either expressly or inherently described, in a single prior art reference." *Verdegaal Bros. v. Union Oil Co. of California*, 814 F.2d 628, 631, 2 USPQ2d 1051, 1053 (Fed. Cir. 1987). In this case, the *Moriya* reference cited by the Examiner fails to either explicitly or implicitly teach or suggest each and every element of the rejected claims.

#### **A. The cited reference, *Moriya* does not teach or suggest each and every element of independent claims 1, 23, 31, 36 and 37**

##### Claims 1-8

Claim 1 is directed to a method of generating a three-dimensional scene from a sequence of two-dimensional images. More particularly, claim 1 recites:

A method of recovering a three-dimensional scene from two-dimensional images, the method comprising:  
providing a sequence of images;  
dividing the sequence of images into segments;  
performing three-dimensional reconstruction for each segment individually; and  
combining the three-dimensional reconstructed segments together to recover a three-dimensional scene for the sequence of images. (Emphasis added).

*Sub-figures constituting a single basic figure as taught by Moriya do not teach or suggest a method of recovering a three-dimensional scene from a sequence of two-dimensional images*

by “providing a sequence of images” and “dividing the sequence of images into segments.” The Examiner relies on element 4038 of FIG. 40 of *Moriya* described at column 29, lines 28-31, which refers to “features of a basic figure 4038 constituting a three-dimensional model concerning sub-figures such as points, lines, planes, type of a cube, a classification of a linear line and a curved line or the like.” See e.g., Office action mailed April 23, 2003, at page 2 (alleging that column 29, lines 28-31 of *Moriya* teaches or suggest “dividing the sequence of images into segments” and rejecting claims 1-37). The Applicants respectfully disagree.

Among other things, *Moriya* is directed to methods and apparatus for generating 3D models and more particularly to instantaneously and interactively determining a 3D structure and camera parameters of an object from a single two dimensional image not a “sequence of images” as claimed. For instance, the Abstract section of *Moriya* states:

Disclosed is an image processing arrangement to determine camera parameters and make a three-dimensional shaped model of an object from a single frame picture image in an easy manner in an interactive mode. (Emphasis added).

In fact, the specification of *Moriya* is replete with statements to the effect that the methods and apparatus taught therein are particularly advantageous over the prior art because 3D structure and camera parameters associated with an object may be extracted by processing a single 2D image. For example, the Summary of the Invention section of *Moriya* at column 3, lines 49-52 state as follows:

Yet a further object of the preferred embodiment of the present invention is to provide a simplified method/arrangement for determining camera parameters from a single frame picture. (Emphasis added).

The fact that *Moriya* is directed to processing of a single 2D image or frame as opposed to “a sequence of images” is made clearer in the passages relied on by the Examiner for rejecting the subject claims. The passages of *Moriya* relevant to describing FIG. 40 and relied on by the Examiner state at column 29, lines 31-38 as follows:

A unique and novel advantage of the device/procedure of the present invention is that camera parameters and three dimensional CG model data can be determined directly using only a single actual image and further, data determined with the present invention can be cooperatively processed with other (complementary) CG model making software 4040 such as a general-used CAD device. (Emphasis added).

Moreover, the passage goes on distinguish what *Moriya* clearly considered to be the invention from those processes that may rely on multiple image frames (e.g., the recited “sequence of images”). The relevant passage at column 29, lines 46-52 states:

It is important to note that within the present invention, determination of camera parameters, extraction of 3-D image data of objects and determination of 2-D image data are all preferably and advantageously conducted using a single frame picture image (i.e., as opposed to having multiple differing frames to determine camera positions.)

Thus, at best, “features of a basic figure 4038 constituting ... sub-figures such as points, lines, planes, type of a cube, a classification of a linear line and a curved line or the like” as taught by *Moriya* suggests that a single image (i.e., basic figure) may constitute sub-figures, whereas the claim 1 recites “dividing a *sequence* of images into *segments*.” FIG. 3 of the application clearly shows an input “sequence of images” having multiple images (60) and being divided into “segments” (68) wherein each segment comprises multiple frames which are a subset of the input “sequence of images.” For instance, the specification at page 8, lines 7-14 describes “dividing a *sequence* of images into *segments*” with reference to FIG. 3 as follows:

The sequence of images are divided into segments 68, which are illustrated as segment 1 through segment N, where N is any positive integer. Each segment contains a certain number of frames and the number of frames in each segment may vary in length. For example, segment 1 may contain 100 frames whereas segment N contains 110 frames. As described further below, the number of frames in a segment depends on the ability to track feature points in each frame. Thus, each frame in a given segment will have a minimum number of feature points that are trackable to a base frame in that segment. (Emphasis added).

“A sequence of images” as clearly illustrated in FIG. 3 and defined in the specification is a series of multiple related images and the specification clearly teaches that it is this “sequence” that is divided into “segments,” wherein “each segment contains a certain number of frames and the number of frames in each segment may vary in length.” *See*, specification page 8, lines 8-10. Thus, adapting the Examiner’s view would have the effect of ignoring not only the meaning provided in the specification for the word “sequence” and hence, the phrase “dividing the *sequence* of images into *segments*” but it would also ignore their ordinary meaning. However, the “ordinary and customary meaning” of claim terms and phrases cannot be ignored when construing a claim. *See e.g., CCS Fitness, INC., v. Brunswick Corp.*, 288 F.3d 1359 at 1366, 62



U.S.P.Q.2d (BNA) 1658 at 1669 (Fed. Cir. 2002) (“Generally speaking, we indulge a ‘heavy presumption’ that a claim term carries its ordinary and customary meaning”). The search for the “ordinary and customary meaning” of a claim term begins with a general English language dictionary. *See e.g., Id.* (“Sensibly enough, our precedents show that dictionary definitions may establish a claim term’s ordinary meaning”).

In this case, the Examiner would have us believe that a single “basic figure 4038 constituting... sub-figures such as points, lines, planes, type of a cube, a classification of a linear line and a curved line or the like” is the same as “dividing the *sequence* of images into *segments*”, which completely contradicts the ordinary meaning of the term “sequence.” For instance, the ordinary meaning of the term “sequence” is provided as “a continuous or connected series: as **a.** a group of similar or related elements,” which clearly and unambiguously excludes a single element from forming a “sequence.” *See, Webster’s 3d New Int’l Dictionary* 2071 (3d ed. 1993).

Furthermore, the claim 1 recites “dividing the sequence of images into *segments*,” wherein “each segment contains a certain number of frames and the number of frames in each segment may vary in length.” *See, specification* page 8, lines 8-10. Thus, the “segments” derived by “dividing the sequence of images” comprises “a certain number of *frames*” not “sub-figures such as points, lines, planes, type of a cube, a classification of a linear line and a curved line or the like” as recited in *Moriya*. Here, the Examiner’s interpretation directly contradicts the definition provided in the specification, which is not acceptable. Even if a broad interpretation of the ordinary meaning of “segments” may include “sub-figures” of *Moriya*, such an ordinary meaning may be overcome by the definition clearly set forth in the specification. *See, CCS Fitness, INC.* at 1366 (“the claim will not receive its ordinary meaning if the patentee acted as his own lexicographer and clearly set forth a definition of the disputed claim term in either the specification or the prosecution history”). The term “segments” has been unambiguously defined as containing “a number of frames.” *See e.g., specification* at page 7, lines 13-17. Thus, dividing a single image into component elements “such as points, lines, planes, type of a cube, a classification of a linear line and a curved line or the like” as taught by *Moriya*, is not the same as “dividing the *sequence* of images into *segments*” containing a subset of the longer sequence to simplify the processing necessary to reconstruct a three-dimensional scene from a sequence of two-dimensional images.

*Moriya* makes it abundantly clear that its methods and apparatus are directed to processing a single image. Thus, *Moriya* has no need for and thus does not teach or suggest “providing a *sequence* of images” and “dividing the *sequence* of images into *segments*.” Even if one was to argue that the passages cited above from *Moriya* were directed to describing the only preferred embodiment that cannot overcome the fact that *Moriya* fails to teach or suggest “providing a *sequence* of images” and “dividing the *sequence* of images into *segments*.” Adapting the Examiner’s definitions for the phrase “sequence of images” and the term “segments” would directly contradict the definitions clearly set forth in the specification. Furthermore, in case of the term “sequence,” Examiner’s definition would also contradict the “ordinary and customary” meaning of the term.

Since *Moriya* fails to teach or suggest each and every element of claim 1, the rejection of claim 1 under 35 U.S.C. § 102 (e) over *Moriya* is improper and claim 1 in its present form should be patentable. Claims 2-8 depend on claim 1 and at least for the reasons set forth regarding claim 1 they also should clearly be patentable over the cited reference.

### **Claims 23-30**

Amended claim 23 is also directed to a method of recovering a three dimensional scene from a sequence of two-dimensional images. More particularly, claim 23 recites:

A method of recovering a three-dimensional scene from a sequence of two-dimensional frames, comprising:

- (a) segmenting the sequence of two-dimensional frames;
- (b) identifying feature points in at least a first base frame in a first segment;
- (c) analyzing a second frame in the segment to identify the feature points in the second frame;
- (d) determining whether a threshold number of feature points from the base frame are identified in the second frame;
- (e) if a threshold number of feature points are identified in the second frame, adding the second frame to the segment; and
- (f) repeating (c) through (e) for subsequent frames until the number of feature points in a frame falls below the threshold number. (Emphasis added).

As amended, claim 23 recites “A method of recovering a three-dimensional scene from a sequence of two-dimensional frames, comprising: *segmenting the sequence of two-dimensional*

*frames.*” (Emphasis added). Thus, at least for the reasons set forth above with regard to claim 1, claim 23 and its dependent claims 24-30 should also be patentable.

### **Claims 31-35**

Claim 31 is directed to an improvement in the method of recovering a three-dimensional scene from a sequence of two-dimensional frames. More particularly, claim 31 recites as follows:

In a method of recovering a three-dimensional scene from a sequence of two-dimensional frames, an improvement comprising dividing a long sequence of frames into segments and reducing the number of frames in each segment by representing the segments using between two and five representative frames per segment, wherein the representative frames are used to recover the three-dimensional scene and remaining frames are discarded so that the three-dimensional scene is effectively compressed. (Emphasis added).

Claim 31 recites “In a method of recovering a three dimensional scene from a sequence of two-dimensional frames, an improvement comprising *dividing a long sequence of frames into segments.*” Thus, at least for the reasons set forth above with regard to claim 1, claim 31 and its dependent claims 32-35 should also be patentable.

### **Claim 36**

Claim 36 is directed to a computer-readable medium having computer-executable instructions for performing a method of recovering a three-dimensional scene from a sequence of two-dimensional frames. More particularly, claim 36 recites as follows:

A computer-readable medium having computer-executable instructions for performing a method comprising:  
providing a sequence of two-dimensional frames;  
dividing the sequence into segments;  
calculating a partial model for each segment that includes three-dimensional coordinates and camera pose for features within the frames;  
extracting virtual key frames from each partial model, the virtual key frames having three-dimensional coordinates for the frames and an uncertainty associated with the frames; and  
bundle adjusting the virtual key frames to obtain a complete three-dimensional reconstruction of the two-dimensional frames. (Emphasis added).

Claim 36 recites “providing a sequence of two-dimensional frames” and “dividing the sequence into segments.” Thus, at least for the reasons set forth above with regard to claim 1, claim 36 should also be patentable.

### **Claim 37**

Claim 37 is directed to an apparatus for recovering a three dimensional scene from a sequence of two-dimensional frames by segmenting the sequence of frames. More particularly, claim 37 recites as follows:

An apparatus for recovering a three-dimensional scene from a sequence of two-dimensional frames by segmenting the frames, comprising:  
means for capturing two-dimensional images;  
means for dividing the sequence into segments;  
means for calculating a partial model for each segment that includes three-dimensional coordinates and camera pose for features within the frames;  
means for extracting virtual key frames from each partial model; and  
means for bundle adjusting the virtual key frames to obtain a complete three-dimensional reconstruction of the two-dimensional frames. (Emphasis added).

Claim 36 recites “means for dividing the sequence into segments.” Thus, at least for the reasons set forth above regarding claim 1, claim 37 should also be patentable.

### **B. The cited reference, *Moriya* does not teach or suggest each and very element of independent claim 9**

Claim 9 recites a method of recovering a three-dimensional scene from a sequence of two-dimensional images. More particularly, claim 9 recites as follows:

A method of recovering a three-dimensional scene from two-dimensional images, the method comprising:  
identifying a sequence of two-dimensional frames that include two-dimensional images;  
dividing the sequence of frames into segments, wherein a segment includes a plurality of frames;  
for each segment, encoding the frames in the segment into at least two virtual frames that include a three-dimensional structure for the segment and an uncertainty associated with the segment.

*Sub-figures constituting a single basic figure as taught by Moriya do not teach or suggest a method of recovering a three-dimensional scene from a sequence of two-dimensional images*

by “dividing the sequence of frames into segments, wherein a segment includes a plurality of frames.” As he did with regard to claim 1, the Examiner relies on element 4038 of FIG. 40 of *Moriya* described at column 29, lines 28-31, which refers to “features of a basic figure 4038 constituting a three-dimensional model concerning sub-figures such as points, lines, planes, type of a cube, a classification of a linear line and a curved line or the like.” See e.g., Office action mailed April 23, 2003, at page 2 (using the same rationale for rejecting both claim 1 and claim 9). As noted above, in the argument with regard to claim 1, *Moriya* is focused on processing a single frame and thus, has no need for and does not teach or suggest “dividing the sequence of frames into segments, wherein a segment includes a plurality of frames.” First of all, the specification makes it amply clear that “segments” comprise “a certain number of frames.” See, specification page 8, lines 8-10. However, the additional limitation of claim 9 which recites “wherein a segment includes a plurality of frames” makes it abundantly clear that segments comprise of frames not “sub-figures such as points, lines, planes...” Thus, “dividing the sequence of frames into segments, wherein a segment includes a plurality of frames” cannot be anticipated by *Moriya*’s “sub-figures such as points, lines, planes, type of a cube, a classification of a linear line and a curved line or the like.”

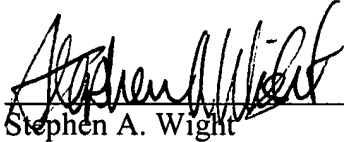
According to the Examiner, “sub-figures such as points, lines, planes...” are “segments” into which “a basic figure” is divided. Adopting, this interpretation would simply ignore the claim limitation that “a segment includes a plurality of frames” or it would mean that “sub-figures such as points, lines, planes...” are the same the claimed “plurality of frames.” However, claim 9 itself claims frames as something larger than “sub-figures such as points, lines, planes...” In fact, claim 9 specifies frames “as a sequence of two-dimensional frames that include two-dimensional images.” A plain reading of claim 9 will not allow the interpretation relied on by the Examiner. Thus, the rejection of claim 9 under 35 U.S.C. § 102 (e) over *Moriya* is improper for this reason in addition to the arguments set forth above regarding claim 1.

**IX. CONCLUSION**

In light of the arguments presented above the rejection of claims 1-37 should be reversed and all claims passed to issue.

Respectfully submitted,

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**APPENDIX A**  
**CLAIMS ON APPEAL**

1. A method of recovering a three-dimensional scene from two-dimensional images, the method comprising:

providing a sequence of images;  
dividing the sequence of images into segments;  
performing three-dimensional reconstruction for each segment individually; and  
combining the three-dimensional reconstructed segments together to recover a three-dimensional scene for the sequence of images.

2. The method of claim 1 wherein performing includes creating virtual key frames for each of the segments, wherein the virtual key frames are only a subset of the images in a segment but are a representation of all of the images in that segment.

3. The method of claim 1 wherein the images contain feature points and a number of images included in a segment is based upon a number of feature points tracked between the images in that segment.

4. The method of claim 1 wherein performing further includes:  
performing a two-frame structure-from-motion algorithm to create a plurality of local models for each segment; and  
combining the plurality of local models by eliminating scale ambiguity.

5. The method of claim 4 further comprising:  
bundle adjusting the combined local models to obtain a partial three-dimensional model for each segment;

extracting virtual key frames from the partial three-dimensional model, wherein the virtual key frames include three-dimensional coordinates for the images and an associated uncertainty; and

bundle adjusting all segments to obtain a complete three-dimensional model.

6. The method of claim 1 further including:  
identifying feature points in the images;  
estimating three-dimensional coordinates of the feature points; and  
estimating a camera rotation and translation for a camera that captured the sequence of images.

7. The method of claim 1 wherein combining includes performing a non-linear minimization process across the different segments through bundle adjustment.

8. A computer-readable medium having computer-executable instructions for performing the method recited in claim 1.

9. A method of recovering a three-dimensional scene from two-dimensional images, the method comprising:

identifying a sequence of two-dimensional frames that include two-dimensional images;  
dividing the sequence of frames into segments, wherein a segment includes a plurality of frames;

for each segment, encoding the frames in the segment into at least two virtual frames that include a three-dimensional structure for the segment and an uncertainty associated with the segment.

10. The method of claim 9 wherein dividing includes:  
identifying a base frame;  
identifying feature points in the base frame; and  
defining the segments such that every frame in a segment has at least a predetermined percentage of feature points identified in the base frame.

11. The method of claim 9 wherein the segments vary in length and wherein the length is associated with the number of frames in the segment.



12. The method of claim 9 further including:  
identifying feature points in the sequence of two-dimensional frames;  
estimating three-dimensional coordinates for the feature points; and  
estimating camera rotation and translation for the feature points.
13. The method of claim 12 wherein estimating the three-dimensional coordinates includes applying a two-frame structure-from-motion algorithm to the sequence of two-dimensional frames.
14. The method of claim 9 further including:  
dividing a segment into multiple frame pairs;  
applying a two-frame structure-from-motion algorithm to the multiple frame pairs to create a plurality of local models; and  
scaling the local models so that they are on a similar coordinate system.
15. The method of claim 14 wherein each of the multiple frame pairs includes a common base frame and one other frame in the segment.
16. The method of claim 15 further including interpolating frames between the multiple frame pairs.
17. The method of claim 9 wherein encoding includes:  
choosing at least two frames in the segment that are at least a threshold number of frames apart;  
for each of the at least two chosen frames, projecting a plurality of three-dimensional points into a corresponding virtual frame; and  
for each of the at least two chosen frames, projecting an uncertainty into the corresponding virtual frame.
18. The method of claim 9 further including bundle adjusting the virtual frames from the segments to create a three-dimensional reconstruction.

19. The method of claim 9 further including identifying feature points in the frames by using motion estimation.

20. The method of claim 19 wherein the motion estimation includes:  
creating a template block in a first frame including a feature point and neighboring pixels adjacent the feature point;  
creating a search window used in a second frame; and  
comparing an intensity difference between the search window and the template block to locate the feature point in the second frame.

21. The method of claim 9 wherein at most two virtual frames are used.

22. A computer-readable medium having computer-executable instructions for performing the method recited in claim 9.

23. A method of recovering a three-dimensional scene from a sequence of two-dimensional frames, comprising:

- (a) segmenting the sequence of two-dimensional frames;
- (b) identifying feature points in at least a first base frame in a first segment;
- (c) analyzing a second frame in the segment to identify the feature points in the second frame;
- (d) determining whether a threshold number of feature points from the base frame are identified in the second frame;
- (e) if a threshold number of feature points are identified in the second frame, adding the second frame to the segment; and

(f) repeating (c) through (e) for subsequent frames until the number of feature points in a frame falls below the threshold number.

24. The method of claim 23 further including designating a frame that falls below the threshold number as a base frame in a second segment and repeating (b) through (e) for the second segment.

25. The method of claim 23 further including performing motion estimation to identify the feature points.

26. The method of claim 23 further including using corners as the feature points.

27. The method of claim 23 wherein the number of frames varies between segments.

28. The method of claim 23 further including creating two virtual key frames per segment.

29. The method of claim 28 further including bundle adjusting the virtual key frames of all the segments to obtain a three-dimensional reconstruction.

30. A computer-readable medium having computer-executable instructions for performing the method recited in claim 23.

31. In a method of recovering a three-dimensional scene from a sequence of two-dimensional frames, an improvement comprising dividing a long sequence of frames into segments and reducing the number of frames in each segment by representing the segments using between two and five representative frames per segment, wherein the representative frames are used to recover the three-dimensional scene and remaining frames are discarded so that the three-dimensional scene is effectively compressed.

32. The method of claim 31 wherein each of the representative frames have an uncertainty associated therewith.

33. The method of claim 31 wherein the long sequence includes over 75 frames.

34. The method of claim 31 wherein dividing the long sequence into segments includes identifying a base frame and tracking feature points between frames in the sequence and the base frame and ending a segment whenever a frame does not contain a predetermined threshold of feature points that are contained in the base frame.

35. The method of claim 31 further including performing a two-frame structure-from-motion algorithm on each of the segments to create a partial model.

36. A computer-readable medium having computer-executable instructions for performing a method comprising:

- providing a sequence of two-dimensional frames;
- dividing the sequence into segments;
- calculating a partial model for each segment that includes three-dimensional coordinates and camera pose for features within the frames;
- extracting virtual key frames from each partial model, the virtual key frames having three-dimensional coordinates for the frames and an uncertainty associated with the frames; and
- bundle adjusting the virtual key frames to obtain a complete three-dimensional reconstruction of the two-dimensional frames.

37. An apparatus for recovering a three-dimensional scene from a sequence of two-dimensional frames by segmenting the frames, comprising:

- means for capturing two-dimensional images;
- means for dividing the sequence into segments;
- means for calculating a partial model for each segment that includes three-dimensional coordinates and camera pose for features within the frames;
- means for extracting virtual key frames from each partial model; and

means for bundle adjusting the virtual key frames to obtain a complete three-dimensional reconstruction of the two-dimensional frames.

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# Table

Lexical and Ele	
Preface . . . . .	
Noah Webster	
Explanatory Di	
Explanatory N	
A Concise Gui	
Style Guide . .	
Problems in En	
Clichés . . . . .	
Redundant Exp	
Students' Gui	
Business Lette	
Forms of Addr	
Abbreviations	
Pronunciation	
A New Dictio	
Abbreviations	
Biographical N	
Geographic N	
Foreign Words	
Table of Meas	
Signs and Syn	

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ing: STEP <runs with a light foot> 8. Foot soldiers. 9. The attack.

10. A mechanical unit consisting of a stressed or unstressed syllable of the language. 11. A unit of length in the U.S. Customary and British Imperial systems, equal to  $1/8$  yard or 12 inches. 12. Feet. Sediment that forms during the refilling of a ditch.

**footed, foot-ing, foots.** —**Vt. 1.** To go on foot; **WALK**. **2.** To dance.  
—**Vr. 1.** To go by foot over, on, or through; **TWALK**. **2.** To provide  
(e.g., a stocking) with a foot. **3.** To add (a column of numbers) and  
write the total at the bottom; **TOTAL**. *<foot in the butt>*

to pay < Can you foot the bill? > —*on foot*. Walking or standing. —*put (one's) best foot forward*. Informal. To make a good beginning or favorable first impression. —*put (one's) foot down*. Informal. To assert one's will emphatically. —*put (one's) foot in (one's)*.

**footage** (fōt'ch) *n.* 1. Length or extent, expressed in feet. 2. A segment of motion-picture film, esp. a segment depicting a particular type of action or scene. 3. A scene or sequence of scenes in a motion picture. *Informal:* To make a tactless or embarrassing blunder in speech.

**mouth-and-mouth disease** (dot=sn-mouth) *n.* An acute, highly contagious degenerative but usu. nonfatal viral disease of cattle and other cloven-footed animals, marked by fever and the eruption of vesicles around the mouth and hoofs.

**FOOTBALL (soccer)** *n.* 1. A game played by two teams of 11 players each on a rectangular, 100-yard-long field with goal lines and openings at either end, the object being to gain possession of the ball and advance it in running or passing play across the opponent's goal line by kicking or striking it with the foot. 2. A smaller game played by two teams of 7 players each on a rectangular, 50-yard-long field with goal lines and openings at either end, the object being to gain possession of the ball and advance it in running or passing play across the opponent's goal line by kicking or striking it with the foot.

field 110 yards long. c. The inflated oval ball used in either of these games. 2. *Chiefly Brit.* a. Rugby football. b. The ball used in Rugby football. 3. *Chiefly Brit. & Soccer.* b. The ball used in soccer. 4. A problem or issue passed about more.

ly written, < The court appointment became a political football. > foot-board (foot'board', -board) n. 1. A board, or small raised platform on which to support, or rest the feet, as in a carriage. 2. An upright board across the foot of a bedstead.

**foot-bridge** (fōot'brīj) *n.* A pedestrian bridge.

**foot-candle** (fōot'kandl) *n.* *Physics.* The illumination of a surface one foot distant from a source of one candle, equal to one foot-candle per square foot.

1. A richly ornamented cloth draped over the back of a horse and touching the ground. 2. Or a carpet or rug.

**foot** (*fōot*) *n.* 1 A measure to take prompt or re-  
acted (*fōot'd adl.* 1 Having a foot or feet. 2 Having a given kind  
number of feet: <web-footed>  
number (fōot'z) *n.* 1 A pedestrian. 2 One measured by an indi-

number of feet in height or length < a five-footer >  
 2. A football. 3. The sound of a footstep.  
 4. A fault against the server, as in tennis, called for  
 when to keep both feet behind the base line.

**foot-hill** (fōt'hil) *n.* A low hill close to the base of a mountain or mountain range.

2. A surface or the condition of a surface with respect to the condition with which one may walk or run on it  $\leq$  Poor footing on the surface.

to use supporting base or groundwork of a structure, as for a sidewalk or wall 4. a. A basis; foundation < a business began on solid footings > b. A basis for social or business transactions with individuals < an equal footing with other executives > 5. a

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Preface . . . . .  
Editorial Staff  
Outside Consu  
Explanatory C  
Explanatory N  
Divisions in B  
Spelling . . . . .  
Plurals . . . . .  
Capitalization  
Italicization . .

egs electromag  
Afro-Asiatic la  
alphabet table.  
anthracite coal  
architecture . . .  
common area  
Beaufort scale  
ship's bells . . .  
book sizes . . . .  
Braille alphab  
constellations .  
chief crusades  
principal ocea  
executive U.S  
dye tables I a  
Easter dates .  
chemical elem  
four syllogisti  
principal railr  
common shot  
geologic time  
géstation peri  
glacial epoch:  
incubation pe  
Indo-Europea.  
measures and

Color:  
Two plate  
Constellation  
Constellation

